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Blowing in the wind: III. Accretion of dust rims by chondrule-sized particles in a turbulent protoplanetary nebula

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Abstract

The fabric of primitive meteorites is dominated by small but macroscopic particles—chondrules, refractory mineral inclusions (CAIs), metal grains, and their like. One interesting aspect of these particles is that they are often surrounded by well-attached rims of fine-grained dust which appear to have been "accreted" onto solid mineral cores. The rim thickness varies from one meteorite to another, but there seems to be a proportionality between the thickness of the rim and the size of the core. We make use of recently derived analytical expressions for absolute and relative velocities of chondrule-and-CAI-sized particles in a weakly turbulent nebula (Cuzzi and Hogan, 2003, paper I of this series) to assess the acquisition of fine-grained accretionary dust rims by particles in the chondrule-to-CAI size range. We compare these predictions with meteoritic observations, and show how the existence of fairly compact dust rims on chondrules and similar size objects can be easily understood within the turbulent nebula context. We estimate the time needed to accrete such rims to be in the 10^2–10^3 year range. More observations of the form of the correlation between rim and core diameter in dust-rimmed chondrules are needed in order to strongly constrain the environment and history of these objects.
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1. Background

The fabric of the most primitive meteorites undoubtedly contains many clues as to their origin. While most chondrites are samples of surfaces that have been well worked over by impacts and stirring ("regolith breccias"), the original dominance of chondrules and like-sized objects remains clear. How it came about that most chondrite parent bodies are so dominated by particles with such a well-defined range of physical, chemical, and petrographic properties remains one of the big puzzles of meteoritics.

Fe–Mg–Si–O mineral chondrules, which solidified from a melt, constitute 30–80% of primitive meteorites. There are a number of extant hypotheses for the formation of the chondrules. Most workers in the field believe that chondrules are formed by either localized or nebula scale energetic events operating on freely floating precursors of comparable mass, at some location or locations in the protoplanetary nebula (see, e.g., Grossman (1989), Grossman et al. (1989), Boss (1996), Connolly and Love (1998), and Jones et al. (2000) for reviews of hypotheses on this long-controversial and perennially fascinating subject).

Another meteorite constituent of great interest are the mineral grains called Ca–Al-rich refractory inclusions (CAIs)—so-called because their constituent minerals condense out of nebula gas at a much higher temperature than do chondrules. These objects are widely believed to be direct nebula condensates, and have a complex subsequent thermal history which has some similarities to that of chondrules and some differences. They make up 1–10% of primitive meteorites depending on type, and their size distribution is broader than that of the chondrules. There is increasing evidence from radioisotope ages that CAIs are $\geqslant 10^6$ years older than the chondrules. How these old, high-temperature minerals find themselves intimately mixed with lower-temperature minerals remains a puzzle. Surely, their nebula evolution must share at least some similarities with the chondrules they share the same parent body with. Some, for instance, also have rims of fine-grained dust.

Fine dust, such as comprises fine grained chondrule rims, is well trapped to the nebula gas, so the relative velocity of a particle *through* the gas causes it to encounter fine grained

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Nomenclature

c	gas molecule thermal speed
CV, CM	carbonaceous chondrite types
E_R	collision energy to restructure a fluffy aggregate
$E_{\max}$	collision energy for maximum compaction of a fluffy aggregate
E_D	collision energy to disrupt and disperse a fluffy aggregate
f_{co}, f_{do}	initial chondrule and dust mass fractions
H	nebula vertical scale height
l	eddy size
L	integral or largest scale in turbulent energy spectrum
n_m	number monomers in a fluffy aggregate
OC	ordinary chondrite
p	power of V_{pg} dependence on particle size
r, r_1	particle radius; radius at $St_\eta = 1$
r_c	radius of chondrule or core of rimmed chondrule
r_m	radius of monomer or rim grain
Re	flow Reynolds number
St_L	Stokes number relative to largest eddy
St_η	Stokes number relative to Kolmogorov scale eddy
t_s	stopping time of particle due to gas drag
$t_e(l)$	overturn time of eddy with size l
t_L	overturn time of largest eddy
t_{rim}	general rimming timescale (Eqs. (5), (14))
t_a, t_b, t_d	various scaling times: Eqs. (8), (9), and (16)
t^*	dust depletion time: Eq. (17)
t_η	overturn time of Kolmogorov scale eddy
V_{rim}	volume of fine-grained accretion rim
V_{core}	volume of underlying chondrule
V_g	gas turbulent velocity (large eddy)
V_p	particle random velocity in inertial space
V_{pg}	relative velocity between particles and gas
V_{pp}	relative velocity between particles
α	nebula viscosity parameter; $Re = \alpha c H/\nu$
η	Kolmogorov scale
ν	molecular kinematic viscosity
ν_T	turbulent kinematic viscosity
Ω	orbital frequency
ω	eddy frequency
ρ_d	ambient dust density
ρ_{co}, ρ_{do}	initial mass density of chondrules and dust
ρ_s	mean particle mass density
ρ_g	gas mass density
ρ_{do}	mass density of dust in the nebula
ρ_{co}	mass density of chondrules in the nebula
ρ_{rim}	mass density of fine grained chondrule rim
ξ	sticking coefficient of grains to rimmed chondrule
ζ	chondrule rim volume/core volume

dust. The questions are then, does that dust accrete onto the surfaces of chondrules and CAIs, and what are the resulting properties of the accretion rims? The outcome depends on the magnitude of the relative velocity and the physical properties of the grains and the particle surface.

For the purpose of this paper, we presume that chondrules and CAIs form in the nebula, while remaining neutral on the details of their formation, and concentrate on their post-formation evolution. In two recent papers we have described the velocities of small particles in a turbulent gas (Cuzzi and Hogan, 2003) and the formation and radial diffusion of CAIs (Cuzzi et al., 2003). In this paper we focus on the accretion of fine grained dust rims by these particles during their nebula phase, prior to their accretion into parent bodies (cf. also Cuzzi et al., 1998). In Section 1 we review some relevant meteorite data and provide introductory background on turbulence and how the relative velocity between a particle and the gas (and embedded fine-grained dust) is derived. In Section 2 we use our new results for the relative velocity between particles and gas to formulate a model for the formation of fine grained dust rims on chondrules and other, similar sized particles and compare the model predictions with the observations. This model makes use of a sub-model for rim porosity and grain sticking, which we develop and present in Section 3. In Section 4 we combine the results of Sections 2 and 3, and explore the time needed for particles to acquire the observed rims, as well as more general implications for the primary accretion of primitive planetesimals.

1.1. *Meteorite evidence regarding fine grained rims*

Several excellent reviews of fine grained material as rims on coarse particles, and/or as enveloping matrix unassociated with specific particles, are by Scott et al. (1989), Metzler and Bischoff (1996), Brearley (1996), and Brearley and Jones (1998). Fine grained rims are generally more firmly attached to the underlying chondrule than to enveloping matrix, and respond to mechanical disaggregation by coming loose from the enveloping matrix material still firmly bound to their underlying chondrule (Paque and Cuzzi, 1997). Rims and matrix are generally distinguishable texturally in scanning electron microscopy of meteorite thin sections, even though the physical, chemical, and mineralogical properties of the constituent rim and matrix grains tend to be rather similar (Brearley and Jones, 1998, with exceptions, naturally; Taylor et al., 1984; Zolensky et al., 1990). Carbonaceous chondrites (CV, CO, CM) exhibit much thicker rims (> 100 microns) than ordinary chondrites (OC) (less than tens of microns). Most of the rim and matrix grains are various kinds of silicates, but a small fraction are metal or metal sulfide. In CV meteorites, the rim and matrix grains are very similar, and are typically the largest of any class ($\sim 5\mu$ diameter; meteoriticists report grain "sizes" as diameters, and we follow this convention). Rim and matrix grains in CO and CM chondrites are also quite similar to each other ("identical" for COs, according to Brearley, 1993) but smaller in size than for CVs—perhaps $\sim 1\mu$ in size. Regarding ordinary chondrites (OC), Ashworth (1977) observed a dearth of larger grains and grain fragments in chondrule rims, compared to their abundance in the surrounding matrices of these same meteorites. The rim grains span a range of modal size between $\sim 2\mu$ (Hedjaz) through $\sim 0.2\mu$ (Parnallee, Weston) to as fine as 0.06μ in Chainpur (Ashworth, 1977).

In OC, rim porosities are often described as lower than in the surrounding matrix (which Ashworth gives as 6–15%; see also Scott et al., 1989). That is, their densities are lower than "solid" chondrules, but not dramatically so. It is sometimes suggested (e.g., Wasson, 1995) that this modest porosity is incompatible with nebula accretion of rims, because nebula-formed rims might be expected to be highly porous, fairy-castle structures with no durability. However, we contend that the observed properties are actually quite easy to understand in the nebula context.

A key observation was first reported by Metzler et al. (1992); see also Metzler and Bischoff (1996). They found fragments, or clasts, of material within the usual regolith breccias, and even entire meteorites, which seemed to be unbrecciated agglomerates of dust-rimmed chondrules. They refer to these as "primary accretionary rock." The meteorites studied by Metzler et al. were CM2 chondrites—containing chondrules having relatively thick fine-grained rims. In their samples of primary accretionary texture, they found all chondrules and other coarse particles to be surrounded by fine-grained rims, and conversely, that the only fine grained dust present was within these already-accreted rims. Some caution must be applied to these specific rocks, because CMs have been aqueously altered and the rim grains are now collections of hydrated silicates rather than the original anhydrous grains. However, the textural distinction between rims and groundmass remains easy to see in electron micrographs. In addition, similar "primary texture" has been observed in other (less altered, or unaltered CO-type) meteorites as well (cf. Brearley, 1993).

This evidence leads to the inference that the very earliest generation of accumulated particles—the first primitive bodies—contained only dust-rimmed coarse particles (chondrules and the like), and that the more familiar mix of rimmed and fragmented chondrules within a structureless interstitial matrix of fine dust was a result of post-accretional mechanical fragmentation and abrasion of the primary texture on a parent body, during the subsequent collisional evolution that surely occurred (Metzler et al., 1992). In a similar way, in OCs, only samples which have escaped brecciation exhibit rims around all coarse components (Metzler and Bischoff, 1996; Taylor et al., 1984; Allen et al., 1980; Ashworth, 1977).

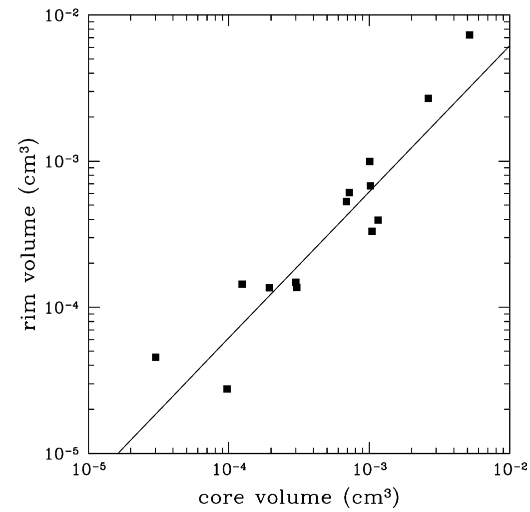

Fig. 1. Chondrule rim volume (thickness) is close to linearly proportional to core volume (radius); data on Allende CV chondrite from Paque and Cuzzi (1997). The line has slope unity, merely for comparison, and is not a best fit of any kind.

Metzler et al. (1992) measured rim thicknesses in thin section on hundreds of CM chondrules. Unfortunately, the thin section techniques used produced a large dispersion in the relationship between core size and rim thickness, making it difficult to infer more than that the rim thickness and core thickness were positively correlated (see also Morfill et al., 1998). To improve on this approach, Paque and Cuzzi (1997) followed the earlier approach of Hughes (1978); they disaggregated, catalogued, weighed and measured individual whole chondrules from a number of different chondrite types. A small number of these were then mounted and ground to reveal the rim in cross section, allowing the true thickness to be determined without the sampling uncertainty of thin section techniques. One preliminary but intriguing result was a well defined, nearly linear relationship between rim volume (thickness) and core volume (radius), with a smaller amount of scatter than in the Metzler et al. data (see Fig. 1). Unfortunately, only a small fraction of Paque's unique chondrule collection data have been studied and reduced, not to mention published. Part of the goal of this paper is to motivate further studies of this or similar data sets. The reason for this, as discussed below, is that a more precise measurement of the slope of the $V_{\rm rim}$ vs. $V_{\rm core}$ relationship can provide critical constraints on the accretion environment.

1.2. Particle–gas interactions

The interaction between a particle and the surrounding gas is determined by the particle stopping time t_s; for particles such as we deal with here, which are smaller than a gas molecular mean free path, the Epstein regime applies (Weidenschilling, 1977):

$$t_s = \frac{r\rho_s}{c\rho_g}, \tag{1}$$

where r is particle radius, ρ_s is particle material density, c is the nebula sound speed, and ρ_g is the nebula gas density (Weidenschilling, 1977).

In a nonturbulent, or *laminar*, nebula where the particle is subject only to a constant acceleration a, the particle–gas relative velocity V_{pg} is simply the terminal velocity at_s. The accretion of fine grained chondrule rims in such a nebula environment was discussed by Morfill et al. (1998), who assumed that the rimming was done as chondrules move at terminal velocity at_s, with $a =$ constant, in what they must have presumed to be a *laminar* nebula. They left the cause of this acceleration open, but it could be gravitational settling in a laminar nebula, gas-drag driven radial drift, or a combination.[1]

In this paper we focus on how the process would work in a weakly *turbulent* nebula. It remains unresolved at this time whether the nebula gas was turbulent or laminar during the chondrule era. In previous papers, we have suggested that some of the observed properties of chondrules themselves—their typical size and size distribution—can be associated with, and easily explained by, the effects of weak nebula turbulence, and argued that turbulence in the sense of fluctuating gas motions and diffusivity, which is of most interest to us, can be present even if turbulent *viscosity*, capable of evolving the nebula, is not (Cuzzi et al., 1996, 2001). Here, for simplicity, we will merely adopt the standard α-model formalism and ignore the distinction between turbulent viscosity and turbulent diffusivity (e.g., Prinn, 1990). A turbulent nebula is characterized by the turbulent gas velocity $V_g = V_L$ on some largest eddy, or integral lengthscale L. The intensity of turbulence can be characterized by the square of the turbulent match number $\alpha = V_g^2/c^2$, where α can be associated with the standard Shakura–Sunyaev parameter and is widely used in nebula modeling. Since the overturn frequency Ω_L of the largest true eddy L is probably comparable to the local Keplerian frequency Ω_o, it can be easily shown that $L^2/H^2 = \alpha$ as well, where H is the vertical scale height of the nebula (see Cuzzi et al., 2001, for more detail). Thus, $L = H\alpha^{1/2}$ and $V_g = c\alpha^{1/2}$. The nebula Reynolds number $Re = LV_L/\nu$, where ν is the molecular viscosity, characterizes the intensity of turbulence; in the α-model formalism $Re = LV_L/\nu = \alpha cH/\nu$. High-*Re* turbulence is characterized by an *inertial range* of lengthscales, from the largest scale L to the smallest, or Kolmogorov scale η. Dimensional arguments alone lead to the relationship $L/\eta = Re^{3/4}$. Energy flows nearly losslessly down this range and is dissipated at the smallest scales. Decades of observations and theoretical work validate the early scaling laws of Kolmogorov which allow us to express the typical fluctuating velocity $v(l)$ and eddy frequency $\omega(l)$ on any scale l as simple powerlaws: $v(l) = V_L(l/L)^{1/3}$ and $\omega(l) = \Omega(L)(l/L)^{-2/3}$ (Cuzzi and Hogan, 2003). The overturn time of an eddy of lengthscale l is just $t_e(l) = 1/\omega(l)$.

Treatment of the interaction of particles and turbulent gas is more difficult than in the laminar case, because the accelerations to which it is subject are those of turbulent eddies, which fluctuate on a variety of timescales $t_e(l)$. The problem was first addressed by Völk et al. (1980), again by Markiewicz et al. (1991), and most recently by Cuzzi and Hogan (2003). Cuzzi and Hogan (2003) (henceforth CH03) presented simple analytical expressions for three kinds of particle velocities in turbulence, based on the approach of Völk et al. (1980) (henceforth VJMR), and Markiewicz et al. (1991) (henceforth MMV). The three kinds of velocities are the inertial space random velocity V_p, the relative velocity between particles and gas V_{pg}, and the relative velocity between comparable size particles V_{pp}.

CH03 emphasized particles with stopping times t_s comparable to the overturn time t_η of Kolmogorov scale eddies. Particles in this size regime have behavior more complex than tiny "dust" grains, which are essentially trapped to the gas flow on all scales. In particular, particles with $t_s = t_\eta$ are subject to "preferential concentration" by large factors in turbulence, and based on some of its apparent fingerprints in the meteorite record, we have suggested a link between this process, chondrules, and primary accretion. Specifically, we refer to the fact that the *typical size* and the *shape of the size distribution* of chondrules are readily explained by turbulent concentration (Cuzzi et al., 1996, 2001).

In a second paper (Cuzzi et al., 2003) we explored how turbulent diffusion and gas-drag-driven radial drift combine to evolve CAIs throughout the nebula over an extended period of several Myr. In a nebula that is even weakly turbulent, the vertical component of gravity is negligible compared to turbulent accelerations from eddies; chondrule-sized particles do not "settle" significantly, but merely diffuse around. In this perspective then, both CAIs and chondrules should show some evidence of an extended nebula evolution.

In the turbulent regime, particle aerodynamic behavior is determined by the Stokes number *St*, the ratio of the particle stopping time t_s to the overturn time of some characteristic eddy. We will make use of Stokes numbers defined relative to two different eddy overturn timescales: the Stokes number relative to the largest, or integral scale eddy time t_L: $St_L = t_s/t_L$, and that defined relative to the smallest, or Kolmogorov scale eddy time t_η: $St_\eta = t_s/t_\eta$. The overturn time of the largest scale eddy t_L is generally regarded as the local orbit period. Preferentially concentrated particles (chondrules, we have suggested) have $St_\eta = 1$ and $St_L \ll 1$. Since $\omega(\eta)/\Omega(L) = (\eta/L)^{-2/3}$, and $\eta/L = Re^{-3/4}$, any particle having $St_\eta = 1$ will also have $St_L = Re^{-1/2}$. For these particles, which are smaller than the gas molecular mean free

[1] A variant was discussed by Liffman and Toscano (2000). In which it was suggested that fine grained rims can accrete in a circumstellar wind reentry environment at relative impact velocities of $V_{pg} > 1$ km/sec. We do not regard this as credible, based on the results of Section 3.

path, the stopping time $t_s = r\rho_s/c\rho_g$ (Eq. (1)); that is, t_s and thus St_L are *linearly proportional to particle radius*. In this paper we suggest that this special relationship might have left fingerprints in the properties of accretionary rims, and indicate ways this might be more carefully tested.

1.2.1. The particle–gas velocity V_{pg}

CH03 discuss the important role of the gas velocity autocorrelation function along a particle trajectory (see also VJMR and MMV). Simple analytical forms are traditionally used, but the form used has implications for the particle-size dependence of particle velocities—particularly V_{pg} of most interest to us here. Past discussions of dust rimming have assumed that $V_{pg}(r) \propto St_L^{1/2}$, as implied by the results of VJMR. However, more recent discussions (MMV, CH03) imply that for small particles, probably including the chondrule-CAI size range, the best autocorrelation function leads to $V_{pg}(r) \propto St_L$. The general form of V_{pg} is (CH03, Eq. (19)):

$$V_{pg}^2 = V_g^2\left[\frac{St_L^2(Re^{1/2}-1)}{(St_L+1)(St_L Re^{1/2}+1)}\right]. \tag{2}$$

The results of CH03 for both V_{pg} and V_{pp} (the interparticle relative velocity for similar-sized particles) are shown in Fig. 2, for three different values of nebula Re. It is simply shown by retaining leading terms that Eq. (2) for V_{pg} results in three separate regimes: $V_{pg} \approx V_g$ for $St_L > 1$, $V_{pg} \propto St_L^{1/2}$ for $Re^{-1/2} < St_L \ll 1$, and $V_{pg} \propto St_L Re^{1/4}$ for $St_L < Re^{-1/2}$. This is confirmed by inspection of Fig. 2. In the special case of $St_\eta = 1$, or $St_L = Re^{-1/2}$ (locations indicated by vertical lines for each Re in Fig. 2), Eq. (2) reduces

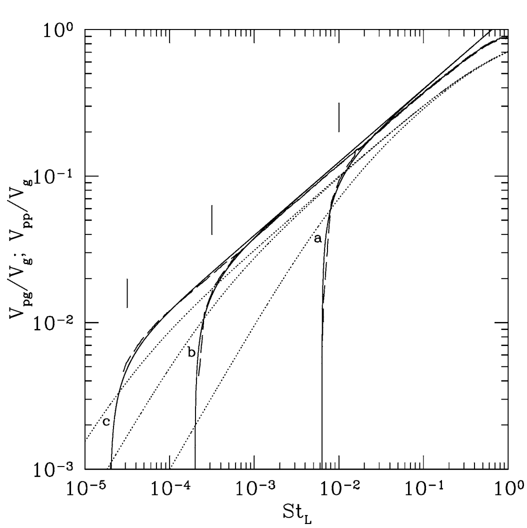

Fig. 2. $V_{pg}(St_L)$ (dotted; Eq. (2)) and $V_{pp}(St_L)$ (solid; CH03, Eq. (24)) for $Re = 10^4$ (a), 10^7 (b), and 10^9 (c). The digitized results of MMV (their Fig. 5) for V_{pp}, for the same three values of Re, are shown by the dashed lines. The V_{pp} expression of CH03 is invalid for $St_L > 0.1$ or so (see text). V_{pp} drops precipitously for $St_L < Re^{-1/2}$ (locations indicated by vertical lines) because no smaller eddies exist to stir random *relative* velocities (MMV, CH03).

directly to

$$V_{pg}(St_\eta = 1) = V_g\frac{Re^{-1/4}}{\sqrt{2}} = c\alpha^{1/4}\left(\frac{\nu}{4cH}\right)^{1/4}, \tag{3}$$

where we have substituted $V_g = c\alpha^{1/2}$ (Cuzzi et al., 2001). The interested reader is referred to CH03 for further details.

Thus, while the particle–gas relative velocity in turbulence is *generally* proportional to $\sqrt{St_L}$ for small St_L, a steeper dependence of V_{pg} on St_L and St_η applies to particles with $St_\eta \leqslant 1$. Bear in mind that $St \propto r$ for the particles of interest. Thus, evidence for a nearly linear dependence of V_{pg} on r, if the environment was turbulent, would imply that the particles in question were $St_\eta \leqslant 1$ particles. This new result derives directly from the use of the improved gas velocity autocorrelation function of MMV and CH03.

2. Rimming of coarse particles by fine dust

2.1. A model for dust rimming

2.1.1. Constant ambient dust density

In a situation where the ambient dust density ρ_d remains constant $= \rho_{do}$, a particle accretes rim mass $m_{\rm rim}$ at the rate

$$\frac{dm_{\rm rim}}{dt} = \pi r^2(t)\rho_{do}V_{pg}\big(r(t)\big)\xi, \tag{4}$$

where $r(t)$ is the instantaneous radius of the rimmed particle, ρ_{do} is the ambient mass density of fine grained dust in the nebula, and ξ is the sticking coefficient (which could, in principle, be negative if net erosion occurs). Thus in some rimming time $t_{\rm rim}$,

$$\begin{aligned} V_{\rm rim}(t_{\rm rim}) &= \int_0^{t_{\rm rim}} \pi r^2(t)\left(\frac{\rho_{do}}{\rho_{\rm rim}}\right)V_{pg}\big(r(t)\big)\xi\,dt \\ &= \int_0^{t_{\rm rim}} \frac{d(\text{vol})}{dt}\,dt, \end{aligned} \tag{5}$$

where we have separated the volume and mass density of the rim. We can then obtain an expression for $r(t)$ as follows:

$$dr(t) = \frac{d(\text{vol})}{4\pi r^2(t)} = \frac{\xi\rho_{do}V_{pg}(r)}{4\rho_{\rm rim}}\,dt. \tag{6}$$

To integrate Eq. (5), we first approximate $V_{pg}(r) = V_1(r/r_1)^p$ where the subscript denotes values at some reference particle radius r_1, which we take as that leading to $St_\eta = 1$; then,

$$\frac{dr}{r^p} = \frac{\xi\rho_{do}V_1}{4\rho_{\rm rim}r_1^p}\,dt \tag{7}$$

with initial condition $r = r_c$ at $t = 0$, where r_c is the radius of the core solid particle. This can be integrated to obtain for $p = 1$:

$$r(t) = r_c e^{t/t_a}, \quad \text{where } t_a \equiv \left(\frac{4\rho_{\rm rim}r_1}{\xi\rho_{do}V_1}\right), \tag{8}$$

and t_a is the characteristic accretion time of Morfill et al. (1998). Similarly, for $p \neq 1$:

$$r(t) = r_c\left(1 + \frac{t}{t_b}\right)^{1/(1-p)},$$

$$\text{where } t_b = \left(\frac{r_c^{1-p}}{1-p}\right)\left(\frac{4\rho_{\rm rim} r_1^p}{\xi \rho_{do} V_1}\right) = \frac{t_a}{1-p}\left(\frac{r_1}{r_c}\right)^{p-1}. \quad (9)$$

Equation (9) reduces to Eq. (8) in the limit $p \to 1$. Simplifying Eq. (5) by assuming ξ and $\rho_{\rm rim}$ are constant, using Eq. (8), and integrating over t, we get for $p = 1$

$$V_{\rm rim}(t_{\rm rim}) = \pi \xi \frac{\rho_{do}}{\rho_{\rm rim}} \int_0^{t_{\rm rim}} r^2(t) V_{pg}\big(r(t)\big)\, dt$$

$$= V_{\rm core}\big[e^{3t_{\rm rim}/t_a} - 1\big], \quad (10)$$

where $V_{\rm core} = 4\pi r_c^3/3$ is the volume of the core. For $p \neq 1$, Eq. (5) becomes (using Eq. (9)):

$$V_{\rm rim}(t_{\rm rim}) = \pi \xi r_c^2 V_1 \frac{\rho_{do}}{\rho_{\rm rim}} \left(\frac{r_c}{r_1}\right)^p \int_0^{t_{\rm rim}} \left(1 + \frac{t}{t_b}\right)^{(2+p)/(1-p)} dt$$

$$= V_{\rm core}\big[(1 + t_{\rm rim}/t_b)^{3/(1-p)} - 1\big]. \quad (11)$$

All prefactors other than $V_{\rm core}$ cancel upon changing variables and integrating by parts. Note that these results show directly how the functional dependence of $V_{pg}(r)$ (through p) affects the dependence of $V_{\rm rim}$ on r_c. For $p \neq 1$ (Eq. (11)), an additional r_c dependence enters in the timescale t_b (Eq. (9)). Only for $p \approx 1$ is the simple proportionality to $V_{\rm core} = r_c^3$ seen (Eq. (10)); expansions show that the timescale t_b has very weak r_c-dependence even for $p \approx 1$.

We will define $\zeta = V_{\rm rim}/V_{\rm core}$ and rearrange the equations to solve for the rimming time after which a given rim volume is accreted; for $p \neq 1$,

$$t_{\rm rim} = \frac{4\rho_{\rm rim} r_c^{1-p} r_1^p}{\rho_{do} \zeta V_1}\big[(1+\zeta)^{(1-p)/3} - 1\big]. \quad (12)$$

Unless $p \approx 1$, this expression has a complicated implicit dependence on r_c, which appears both in the prefactor and in ζ.

We reiterate here the very important fact that, for chondrule-size particles under nebula gas densities, the stopping time t_s is linearly proportional to the product of the instantaneous particle radius $r(t)$ and average particle material density ρ_s (i.e., Eq. (1)):

$$t_s = \frac{r(t)\rho_s}{c\rho_g}. \quad (13)$$

Since CH03 showed that $V_{pg}(r)$ is nearly proportional to St_L in the chondrule size range, and $St_L \propto t_s \propto r$, this means that $p \approx 1$ is just what we would expect for chondrules in weak turbulence. Thus, we can either approximate the above $p \neq 1$ expression in the limit $|p - 1| \ll 1$, or invert the $p = 1$ expression directly, and obtain the same result, valid for $p \approx 1$:

$$t_{\rm rim} = \frac{4\rho_{\rm rim} r_1}{3\xi \rho_{do} V_1} \ln(1 + \zeta). \quad (14)$$

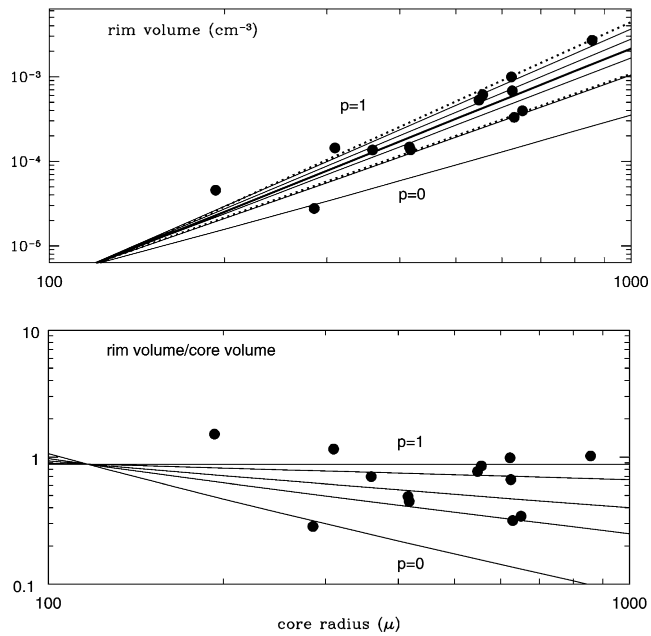

Fig. 3. Rim volume predictions (light weight lines, from Eq. (11)) and observations for Allende (solid symbols; Paque and Cuzzi, 1997, as in Fig. 1). The predictions are for $p = 0$, 0.5, 0.7, 0.9, and 1.0. (Top panel) Direct calculation of rim volume as a function of core radius. (Bottom panel) Rim volume/core volume as a function of core radius. In the top panel we also show a formal least squares fit to the data (heavy solid line) and its formal one-sigma limits (heavy dotted lines).

V_1 and r_1 are taken to be the values of V_{pg} and r where $St_\eta = 1$ exactly (see Eq. (3)). We obtain V_1 from Eq. (3) and we obtain r_1 from Cuzzi et al. (2001, Eq. (8)); at 2.5 AU, $r_1 = 1.3 \times 10^{-4}(\mathcal{F}/\alpha)^{1/2}$ cm, where $\mathcal{F}$ is some mass density enhancement over the minimum mass nebula (we assume $\mathcal{F} = 1$ here). The meaning of $t_{\rm rim}$ in Eq. (14) is that time which *simultaneously* gives *all particles in the observed range of sizes surrounding* $St_\eta = 1$ their observed rim volumes, each proportional to the volume of the underlying core.

In Fig. 3 we compare the rim volume predictions from Eq. (11) for $p = 0$, 0.5, 0.7, 0.9, and 1.0 (light weight lines; $p = 0$ and $p = 1$ are labeled) with the data of Paque and Cuzzi (1997), in two different formats. The solid symbols are the data; the heavy solid line in the top panel is the formal best fit to the data of the function $\log V_{\rm rim} = a \log V_{\rm core} + b$, and the heavy dotted lines represent the range covered by one-sigma uncertainty in a. The models only need to assume $t_{\rm rim}/t_a = 0.2$ and $r_1 = 130\mu$ (as noted above) to approximate the relative rim/core volumes in both panels; other parameters cancel. The formal fit to the limited existing data (heavy line) lies between $p = 0.7$ and $p = 0.9$, but cannot really rule out either $p = 0.5$ or $p = 1.0$. For comparison, a value of $p = 0.75$ is predicted by CH03 for particles with $St_\eta = 1$, as easily found by evaluating the derivative of Eq. (19) of CH03 for $V_{pg}(St)$ at $St_\eta = 1$, where $St_L = Re^{-1/2}$, using the fact that St is proportional to particle radius for chondrules. Thus, our hypothesis that chondrules are indeed $St_\eta = 1$ particles is consistent with the limited current data; about 5–10 times as many points with comparable or smaller variance would probably suffice to confirm or refute the hypothesis.

2.1.2. Variable ambient dust density

Morfill et al. (1998) suggested one way in which all the particles in a meteorite could share the same t_{rim}: specifically, if all the chondrules in some restricted volume of the nebula depleted all the ambient dust in that volume. Below we amplify on the results of Morfill et al. (1998). To keep the math simple, we merely assume a $p = 1$ dependence of $V_{pg}(r)$; our generalized derivations above indicate that our own $p = 1$ rimming equations remain approximately valid as long as p is not too different from unity.

Morfill et al. (1998) showed that the time-dependent ambient dust density $\rho_d(t)$ may be written in the form

$$\frac{\rho_d}{\rho_{do}} = \frac{\rho_o e^{-t/t_d}}{\rho_{co} + \rho_{do} e^{-t/td}}, \tag{15}$$

where

$$t_d = \frac{4 r_1 \rho_{\text{rim}}}{3 \rho_o V_1 \xi} = \left(\frac{\rho_{do}}{3\rho_o}\right) t_a \tag{16}$$

is another timescale which can be associated with the environment, and $\rho_o = \rho_{co} + \rho_{do} = \rho_o(f_{co} + f_{do})$ is the total volume mass density in solids. That is, the initial mass density in chondrules and in dust are ρ_{co} and ρ_{do}, respectively, and f_{co} and f_{do} are their respective fractions of the total mass density in solids, ρ_o. Note that t_d itself is *not* the depletion timescale in general; for instance it is independent of how ρ_o is distributed between dust (f_{do}) and chondrules (f_{co}), and clearly the depletion time must depend on this partitioning. Equation (15) may be crudely approximated as an exponential decay of the dust density by solving for the time $t = t^*$ at which ρ_d/ρ_{do} has fallen to $1/e$; that is,

$$\frac{\rho_d}{\rho_{do}} = e^{-t/t^*} \quad \text{and} \quad t^* = t_d \ln\left(\frac{e - 1 + f_{co}}{f_{co}}\right). \tag{17}$$

Figure 4 shows the exact solution for ρ_d/ρ_{do} (Eq. (15), solid lines) and its crude exponential approximation $\rho_d/\rho_{do} = \exp(-t/t^*)$ (dotted lines).

We continue to follow the Morfill et al. derivation of rimmed particle sizes (their Eq. (7)), using Eq. (15) and generalizing to unequal core density ρ_s and rim density ρ_{rim}. In our notation, the ratio of the final (rimmed particle) radius r to the core radius r_c is

$$\begin{aligned}\frac{r}{r_c} &= \left(1 - f_{do}\left(1 - e^{-t/t_d}\right)\right)^{-\rho_s/(3\rho_{\text{rim}})} \\ &= \left(f_{co}\left(1 - e^{-t/t_d}\right) + e^{-t/t_d}\right)^{-\rho_s/(3\rho_{\text{rim}})}.\end{aligned} \tag{18}$$

Figure 5 shows how r/r_c increases with time, asymptoting on the timescale t^* (dotted lines)—the same timescale on which the ambient dust is depleted—at a particle size r or rim thickness $r - r_c$ which depends only on the initial partitioning of solids into chondrules and dust:

$$\lim_{t \gg t_d} \frac{r}{r_c} = f_{co}^{-\rho_s/(3\rho_{\text{rim}})}. \tag{19}$$

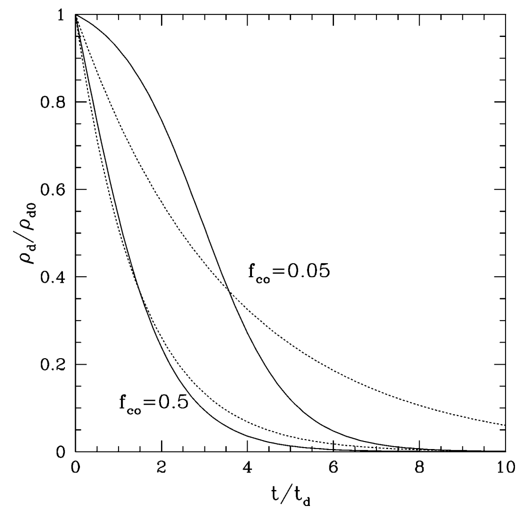

Fig. 4. Depletion of fine grained dust mass density $\rho_d(t)$ in a confined volume by chondrules having two different values of the initial fraction f_{co} of the solid mass. Solid lines: exact expression (Eq. (15)); dotted lines: exponential depletion approximation (Eq. (17)). For $f_{co} = 0.5$, $t^* \sim 1.5t_d$; for $f_{co} = 0.05$, $t^* \sim 3.5t_d$.

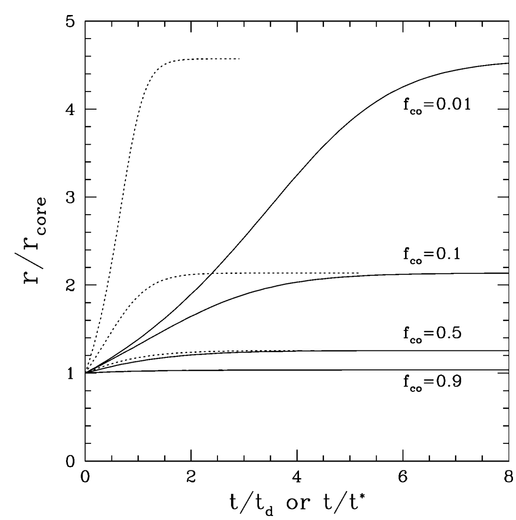

Fig. 5. Growth of particles by rimming in fine dust, for several different initial chondrule mass fractions f_{co}. The histories are plotted against two characteristic timescales: t/t_d (solid) and t/t^* (dotted). Particles growing from smaller values of f_{co} take longer to reach their asymptotic size ($t \approx 6t_d$ for $f_{co} = 0.01$ vs. $t \approx 2t_d$ for $f_{co} = 0.5$); however for each f_{co} the particles asymptote at $t \approx 1.5t^*$. This supports use of t^* as the more useful characteristic timescale.

In Fig. 5 we recall meteoritical data and anticipate the results of the next section by setting $\rho_{\text{rim}} \approx \rho_s$. However, before making quantitative estimates of t_{rim}, t_d, t^*, and other quantities of meteoritical interest, we must address (in the next section) two additional important determining parameters: the sticking coefficient (ξ) and rim density ρ_{rim}.

Summarizing this section, we have derived expressions for rim volume (or final particle radius) as a function of core volume (or radius) which directly reflect the underlying particle-size dependent gas-relative velocity $V_{pg} = V_1(r/r_1)^p$. If $V_{pg} \propto r$, a simple linear proportionality between rim volume and core volume results; if $p < 1$, a flatter dependence results. Particles with $St_\eta < 1$ have a purely linear r-dependence for V_{pg}, and particles with $St_\eta > 1$ have $V_{pg} \propto r^{1/2}$ (Section 1.2.1 see, e.g., Fig. 2). While both these extreme limits lie near the one-sigma formal uncertainties of a best fit to the best existing (very limited) rim volume data, *preferentially concentrated particles*, with $St_\eta = 1$, have an intermediate velocity dependence $V_{pg} \propto r^{0.75}$ that is quite consistent with the data. The data are thus very consistent with the hypothesis that chondrules are indeed $St_\eta \approx 1$ particles, experiencing weak nebula turbulence as described here and in Cuzzi et al. (2001). Additional observations of rim thicknesses which are both more accurate and more precise are needed to distinguish more clearly between the degrees of *near-linear* size dependence. We calculate rim thicknesses under two different assumptions—first, that the ambient dust density remains constant during rim accretion, and second (following Morfill et al., 1998) that the rimming of dust grains occurs in a closed environment, wherein the complete depletion of dust onto chondrule surfaces automatically provides all chondrules in the volume with the same characteristic rim accretion timescale. We explicitly derive the characteristic timescale for this process, t^*, as a function of the initial mass partitioning into chondrules and dust. Quantitatively, however, the rimming times t^* and t_d presented in Section 4 depend on rim density and sticking coefficient, which we address in the next section.

3. Sticking of grains and aggregates

Little is known with confidence about the sticking process, because neither laboratory experiments nor theoretical models provide a high-fidelity representation of nebula materials or conditions. However, it is possible to make "astrophysical accuracy" estimates of what we might expect to occur when chondrules encounter fine grains, based on a combination of theoretical and experimental results.

Theoretical and numerical models by Chokshi et al. (1993) and Dominik and Tielens (1997, and references therein) as updated by subsequent laboratory measurements (Wurm and Blum, 1998, 2000; Heim et al., 1999; Poppe et al., 2000) can be used to get a sense of how grain aggregation proceeds for different materials and relative velocities. Consider monomer grains of mass m and radius r_m. Chokshi et al. (1993) and Dominik and Tielens (1997) (henceforth DT97) showed that the collision kinetic energy $E_c = mV_{\rm rel}^2$ below which sticking of identical grains occurs ($E_{\rm stick}$) is nearly proportional to r_m (their Fig. 18). This means that small grains stick more readily than large ones. Relative velocities between micron-sized grains in plausible nebula turbulence are well below this critical threshold, so we expect fine grains (smaller than a few microns) to form small, fluffy aggregates readily—they stick where they touch. This process is normally referred to as PCA (particle–cluster accretion, see Beckwith et al., 2000, for a review).

DT97 also studied collisions between fluffy aggregates; this is known as CCA or cluster–cluster accretion. They showed, using a model for the deformation of chains and clusters of grains, that two new energy thresholds emerged. For $E_c < E_{\rm res}$, two clusters of mass m simply stick and attach at their first point of contact, just as two monomers would, forming a larger cluster (CCA). For larger collision energies, the aggregates *restructure*, and absorb some energy by deforming chains and *becoming more compact*. That is, after a sufficient number of monomers stick to create a loose fractal aggregate, deformation within this aggregate allows collisions at higher relative velocities to result in sticking and merging of the two aggregates into one denser aggregate. The compacting process proceeds to greater degree and density, until some disruption threshold energy $E_{\rm dis}$, after which point the clusters and/or rim structures begin to be destroyed by the energy of the collision. They showed that these threshold energies could be related to mechanical properties of the grain material and to the size of the monomers. In most cases, DT97 modeled collisions between clusters of $n_m = 100$ monomers. The ability of a cluster to absorb and dissipate energy by deformation, rather than by flying apart or eroding, is, conservatively, proportional to the number of grain contacts $n_c \approx n_m$ involved (DT97, their Fig. 17). Unfortunately, only spherical grains can be modeled, which misses the possibility that irregular grains touch at several different points, but it also misses possibilities where contacts have even smaller radii of curvature than modeled, and are thus even easier to deform. It is an approximate theory for sure, but useful for guidance at the astrophysical accuracy level.

The results of DT97 may be modeled as follows (see DT97, their Fig. 18):

$$E_{\rm res} = \left(\frac{n_m}{100}\right) E_R(1\mu)\left(\frac{r_m}{1\mu}\right) \text{ergs},$$
$$E_{\rm max} = \left(\frac{n_m}{100}\right) E_M(1\mu)\left(\frac{r_m}{1\mu}\right) \text{ergs},$$
$$E_{\rm dis} = \left(\frac{n_m}{100}\right) E_D(1\mu)\left(\frac{r_m}{1\mu}\right)^{4/3} \text{ergs}, \tag{20}$$

where r_m is monomer radius, and $E_R(1\mu), E_M(1\mu)$, and $E_D(1\mu)$ are threshold energies for restructuring, maximum compression, and disruption of aggregates composed of 1μ radius monomers, respectively. These threshold energies are simply related to two different critical energies (for rolling and breaking) as seen in DT97 (their Table 3), and their values can be read directly from Fig. 18 of DT97 for a reduced radius $r_m/2$. There is some evidence that E_D is several times larger for "core–mantle" aggregates (DT97, their Fig. 17), such as might characterize rimmed chondrule surfaces which are our application of interest, so below we apply a factor of 3 to our selection of E_D. In more recent work (Heim et al., 1999; Blum and Wurm, 2000), these very regimes are observed experimentally in the same order and with the same relative threshold velocities. However, quantitatively, the surface energies and velocity thresholds have been found to be larger than assumed by DT97 (also reviewed in Beckwith et al., 2000). Specifically, the energy threshold controlling E_R and E_M is a factor of 18 larger than adopted by DT97 and the energy threshold characterizing E_D is about a factor of 5 larger. Thus we will adopt the following thresholds:

$$\begin{aligned} E_R(1\mu) &= 5.4 \times 10^{-8}\,\text{ergs}, \\ E_M(1\mu) &= 1.8 \times 10^{-6}\,\text{ergs}, \\ E_D(1\mu) &= 1.5 \times 10^{-4}\,\text{ergs}. \end{aligned} \tag{21}$$

Since E_{dis} refers to an aggregate of 100 micron-radius grains, it can be rewritten as 10^5–10^6 erg/g using the above value of E_D, which is comparable, for instance, with values typically used by Weidenschilling (e.g., 1997). Meteorite evidence tells us about the properties of "fine grains" in chondrule rims and the overall enveloping matrix, as described in Section 1.1. The grains are in the micron size range, in general. As discussed above, micron-sized and smaller grains are so strongly tied to the gas that their relative velocity is always extremely small; thus, collisions between micron-sized particles occur only at such slow velocities as readily result in sticking rather than bouncing (Weidenschilling, 1988). Consequently we expect that most grains in the micron size range will quickly form aggregates of similar grains, rather than spending their nebula lifetime as monomers. Chondrules drifting through the gas at relative velocity V_{pg} most likely encounter dust grains not one at a time, but in clusters which are very fluffy, fractal aggregates having the same aerodynamic properties as the monomers of which they are assembled.[2] In an important observation, Brearley (1993, 1996) notes that much of the rim and matrix grain material in two different carbonaceous chondrites can actually be resolved into small clusters or aggregates of grains with noticeably different properties—something like "cluster IDPs" perhaps. This phenomenon is very much along the lines of expectations for nebula aggregation as discussed above, and if so may be true for all samples.

Assuming the (already partially rimmed) chondrule to be of mass far greater than the impinging aggregate, the relevant collisional energy is that of the aggregate, taken as n_m identical monomers of radius r_m and density $\rho_m \sim \rho_s$ (the density of the silicate chondrule itself); thus $E_c = \frac{2}{3} n_m \pi \rho_s r_m^3 V_{pg}^2$. Setting E_c equal to the various threshold energies, we solve for the corresponding critical velocities:

$$\left(\frac{n_m}{100}\right) E_{R,M}(1\mu) \left(\frac{r_m}{1\mu}\right) = E_c \approx 2 n_m \rho_s r_m^3 V_{pg}^2, \tag{22}$$

where n_m cancels leaving

$$V_{pg;R,M}^2 \approx \frac{1.6 \times 10^9 E_{R,M}(1\mu)}{(r_m/1\mu)}. \tag{23}$$

Similarly, for disruption of the aggregate and/or a comparable mass of rim,

$$V_{pg;D}^2 \approx \frac{1.6 \times 10^9 E_D(1\mu)}{(r_m/1\mu)^{5/3}}. \tag{24}$$

Then assuming all monomers are 1μ radius for simplicity, restructuring of fluffy aggregate rims starts at $V_{pg} \sim 10$ cm/sec, maximum compaction occurs near $V_{pg} \sim 50$ cm/sec, and disruption does not occur until V_{pg} exceeds 300 cm/sec or so. These thresholds are consistent with the experiments of Blum and Wurm (2000). It can also be determined from DT97 (their Fig. 18) that the energy threshold at which erosion of monomers starts to play a role is about 18 times lower than the disruption threshold. Poppe et al. (2000) note that irregular particle shapes seem to increase the sticking (disruption) threshold velocity significantly; since rim grains are nonspherical, but equidimensional (Ashworth, 1977) the effect of shape on the restructuring and compaction thresholds is not clear. In addition, triboelectric charging effects (Desch and Cuzzi, 2000; Marshall and Cuzzi, 2001) might play a role. C. Dominik (personal communication, 2002) believes that electrostatic forces, if present, might increase the disruption threshold even further, but will not affect the rolling contacts which control restructuring and compaction. We emphasize that, due to the simplified nature of these estimates, the compaction–disruption energies are probably uncertain by factors of several.

Recall our derivation of the values of V_{pg} expected for chondrules in weak nebula turbulence (Eq. (3)):

$$V_{pg}(St_\eta = 1) = V_1 = c\alpha^{1/4}\left(\frac{\nu}{4cH}\right)^{1/4}. \tag{25}$$

The values of Eq. (25) are plotted in Fig. 6, along with the threshold values of $V_{R,M,D}$ for micron size particles, as well as an "erosion" threshold $V_E \sim V_D/4$, where monomers start to be lost. In this figure (relevant to 2.5 AU) we assume $c = 1.5$ km/sec, $H/R = 0.05$, and molecular viscosity $\nu = 10^6$ cm^2/sec. It is of interest that, over a very wide range of potential values of nebula α, the entire range of velocities we predict for presumably $St_\eta = 1$ chondrules relative to the gas, and thus to monomers or aggregates of monomers, is within the range where highly porous, fluffy structures are compacted, but not disrupted.

More complete future studies should take several factors into consideration. V_{pg} and thus E_c are not really single-valued, but obey a probability distribution function; some collisions are unusually slow, or approach from the trailing side, and might provide those first few sticking events needed to build up a porous "cushion" for subsequent accumulation. Or, the first grains to stick might well be the tiniest in the ambient population, again helping to get the process started. In this sense it might be of interest that OC

[2] Both types of accretion produce grains with fractal dependence of density on size, where the dimension of the fractal is lower for CCA than PCA. For either PCA or CCA, the density of the aggregate drops sufficiently rapidly with increasing size, that the stopping time t_s of the cluster does not increase as it grows; roughly speaking, for such a particle with density decreasing as $1/r$ (cf. Beckwith et al., 2000), the product $r\rho$ (which determines the aerodynamic stopping time) remains constant. Thus aerodynamically, fractal aggregates of this sort behave just like monomers.

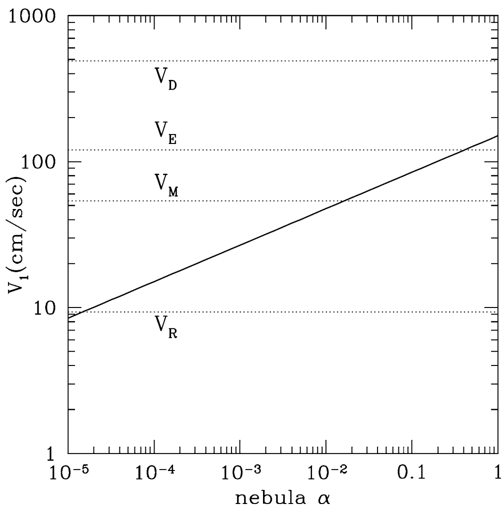

Fig. 6. The relative velocity $V_{pg} = V_1$ (solid line) between particles having $St_\eta = 1$ (assumed to be chondrule size) and the nebula gas with its embedded fine grained dust, for a wide range of candidate nebula α values. Shown by the horizontal dotted lines are threshold velocities for restructuring (V_R), maximal compaction (V_M), erosion of monomers (V_E), and disruption (V_D) of rims composed of swept-up aggregates of micron-radius grains. Note that V_1 is very weakly dependent on α for St_η-sized particles, and its likely values (for $\alpha \sim 10^{-4}$ to 10^{-2}) fall in the range where impinging fluffy aggregates would be accreted and compacted, but not disrupted. Note that for CAIs, which are 5–50 times larger than chondrules, V_{pg} would thus be considerably larger and exceed the erosion threshold for nominal α.

rims at least (which are the thinnest) do tend to be composed of smaller grains than the enveloping matrix. Accretion might *both* compact the rim *and* erode off some of the more loosely bound fingers, creating the rounded configurations we now see. For instance, Lauretta and Buseck (2003) note both the very small grain size in OC rims, and the tendency for rims to be thicker in embayments, which would be protected; a similar tendency is seen in CAIs (see below). There might always be a few fluffy fractal fingers left hanging off any rimmed chondrule, but these delicate structures would quickly lose their identity as rimmed chondrules collide with each other or are abraded in a regolith breccia (or during disaggregation on Earth). The fact that accretionary dust mantles fill in the hollows first and have rounded exteriors, independent of the shape of the core, indicates that perfect sticking is unlikely and that some erosion must also be occurring. This is especially obvious for CAIs (see below). Finally, the low porosity of rims is even more easily explained if the accreting dust grains have a size distribution, as is likely, with smaller grains being able to slip in between larger ones.

Overall, the combination of laboratory and observed properties thus implies that

(a) while some erosion might be occurring, a reasonable sticking probability ξ is justified for chondrules (subsequently we adopt $\xi \sim 0.3$ to within a factor of 3 in either direction), and

(b) it seems reasonable for rims to attain fairly high density as they become compacted by successive incoming grains and aggregates.

3.1. Why are CAIs different?

If the relationship $V_{\rm rim} \propto V_{\rm core}$ persisted from chondrule-sized to CAI-sized particles, we would expect CAIs to have much thicker rims than chondrules. This aspect of CAIs has not been studied systematically, but it seems that while CAIs do show evidence for fine-grained accretion rims (MacPherson et al., 1985; Krot et al., 2002), the rims are thinner, in a relative sense, than for chondrules in the same meteorites (e.g., CVs). Furthermore, the fine grained dust lies preferentially in hollows and cavities in the (often irregular) surfaces of these CAIs. While we will not pursue a detailed model of CAI rimming in this paper, we will point out that the sparse observations to date are compatible with theoretical expectations. Primarily large CAIs have been studied to date. Being larger, these objects have commensurably larger V_{pg}, which places them in the erosive or even disruptive regime (Fig. 6). The fact that accretion rims survive in protected hollows, sometimes to rather significant depth, tends to support the concept that CAI surfaces are sandblasted by virtue of their higher V_{pg}, and accrete rims with more difficulty. Extension to “fluffy” CAIs is more complex because, being fluffy, their t_s is not so simply related to their apparent size. It is not out of the question that their V_{pg} is so *small* for this reason that they might again accrete rims only fairly slowly. In this regard, chondrules might occupy the region of phase space where their V_{pg} is large enough to bring them into contact with a large amount of dust, but small enough to allow them to retain it. More detailed pursuit of these arguments is premature without more actual data on fine-grained rims, but at least the differences between CAI and chondrule rimming do not seem to rule out the perspective advanced here.

4. Predicted values for rimming times

Several groups have estimated rimming times in the past, but their estimates, and the parameters determining them, vary widely. Kring (1988) estimated rimming times of minutes to tens of years. Metzler et al. (1992) estimated tens of thousands of years under highly turbulent conditions ($V_g \sim 0.1c$, or $\alpha = 10^{-2}$), but without any details as to f_{co}, f_{do}, etc.; also Metzler et al. (1991) and (1992) adopted a relationship of $V_{pg} \propto r^{1/2}$ in turbulence, apparently based on the original VJMR results (see Section 1.2.1). They also state that in a quiescent nebula, where settling under gravity produces a linear $V_{pg}(r)$, as in Morfill et al. (1998), the rim formation time was over 10^7 years, much longer than the descent time of several thousand years. This is puzzling because a 100μ radius chondrule encounters 10–50 times more than enough material to make its rim on one vertical descent through such a nebula; however, the details of these calculations have not been published, and are apparently superceded by the work of Morfill et al. (1998), who do not distinguish turbulent from laminar environments, and who do not give a rim formation timescale. It is clear that estimating timescales is very much dependent on the assumed properties of the nebula, the sticking coefficient, one's theories for $V_{pg}(r)$, etc. We feel that, using parameters and relationships derived in the previous sections and papers, we can now estimate chondrule rimming times under different assumptions about the environment, with at least a degree of understanding of the likely range of values and of how parameters affect them.

The rimming time $t_{\rm rim}$ in turbulence, under constant ambient dust density ρ_{do} (Eq. (14)) is plotted in Fig. 7, as a function of α and for several values of $\zeta = $ rim volume/core volume. For this plot and other plots in this section, we assumed a location of 2.5 AU, with gas density 1.1×10^{-10} g/cm^2 and a mass fraction in all solids of $\rho_o = 5 \times 10^{-3}$. We assumed a sticking coefficient $\xi = 0.3$, and a rim density $\rho_{\rm rim}$ which is 90% of the core density $\rho_s = 3.0$ g/cm^3. We used Eq. (3) for V_1 and Eq. (8) of Cuzzi et al. (2001) for r_1—the size of particle which is preferentially concentrated for each value of α. We assumed $c = 1.5$ km/sec and $\nu = 10^6$ cm^2/sec (cf. e.g., Cuzzi et al., 2001). $t_{\rm rim}, t_d$, and t^* can be easily scaled to other values of these parameters. For simplicity in Fig. 7 for $t_{\rm rim}$, we assumed all solids were in the fine dust component ($f_{co} = 0$), because the presumption of invariant ρ_{do} more or less assumes its value is maintained by mixing, or some outside influence, regardless of f_{co}.

The influence of f_{co}, in the case where dust becomes depleted in a restricted volume, is more clearly seen in the following figures. Figure 8 shows t_d (Eq. (16); heavy line) and t^* (Eq. (17); for several values of f_{co}; lighter lines). The

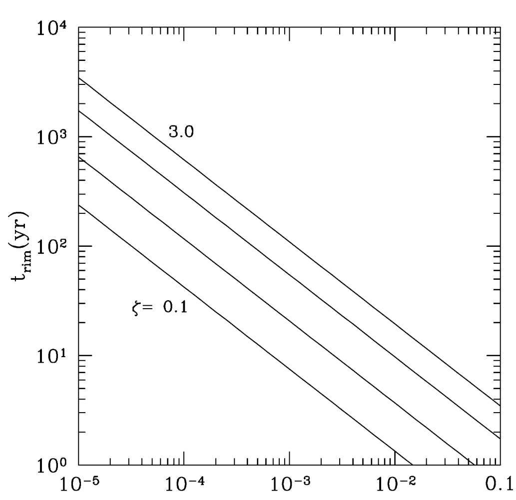

Fig. 7. The rimming time $t_{\rm rim}$ under conditions of constant ambient nebula dust density ρ_{do}, for ζ (rim volume/core volume) = 0.1, 0.3, 1.0, and 3.0. The CM chondrules of Metzler et al. (1992) have $\zeta = 2.4$ and the CV chondrules of Paque and Cuzzi (1997) have $\zeta = 0.7$ (see Fig. 4). Parameters assumed in these curves are given in Section 4.

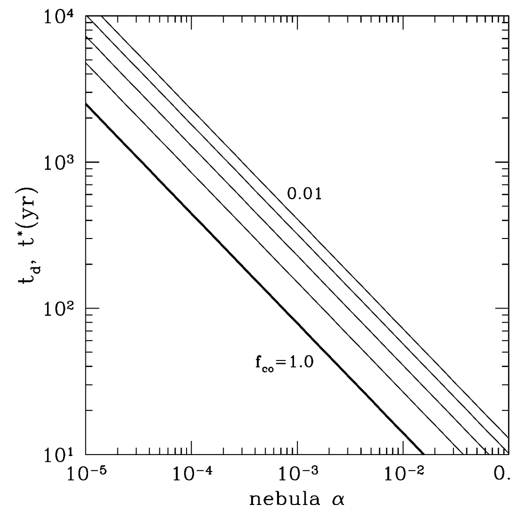

Fig. 8. The depletion times t_d (heavy line) and t^* (light lines) for a scenario in which chondrules deplete all the fine dust in some volume without replenishment. The lines of t^* are for $f_{co} = 0.01$, 0.03, 0.1, 0.3, and 1.0, from top to bottom, and $t^*(f_{co} = 1) = t_d$ (see text, Section 4). Typical rimming times in this scenario are in the 100–1000 year range for plausible values of α which select chondrules for preferential concentration (Cuzzi et al., 2001).

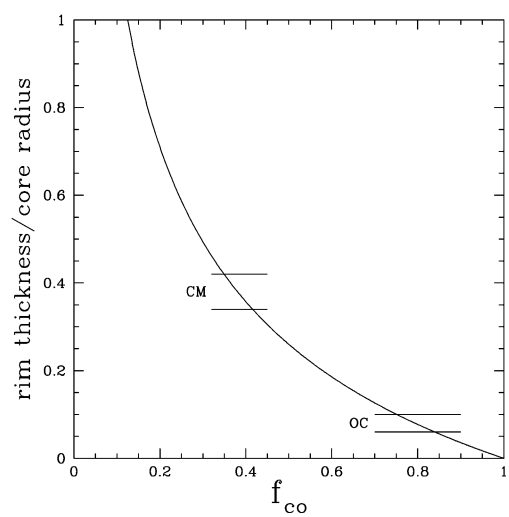

Fig. 9. The asymptotic rim thickness in a dust-depletion rimming scenario as a function of f_{co}. Observed rim thicknesses are shown for CM and OC chondrules (see Section 4).

line for $t^*(f_{co} = 1)$ naturally overlaps the line for t_d. These times are rather longer than $t_{\rm rim}$, since ρ_d is decreasing significantly over the formation time of the rim, but still lie in the 100–1000 year time range for plausible parameters.

If one were to accept or to decide that the "depletion-determined" rimming time condition of Morfill et al. is the case, one can use the observed rim thickness to constrain the initial partitioning of matter into dust and chondrules, as Morfill et al. noted. Recall from Fig. 5, and Eq. (19), that the asymptotic rim thickness is only a function of the initial f_{co}. In Fig. 9 we show this relationship explicitly, along with observed typical rim thicknesses for CM chondrites (Metzler et al. (1992) and Unequilibrated Ordinary Chondrites (OC), Allen et al. (1980)).

5. Implications and speculations

Merging the rimming effects and other processes discussed here with those we have discussed previously (Cuzzi et al., 2001, 2003; CH03) into a self-consistent scenario of primary accretion will take more effort. However, even at this point a few interesting implications of the turbulent nebula premise may be noted.

One interesting comparison is between the dust sweepup times t_d and t^* (Fig. 8, Section 4) and the time it takes for material to diffuse various radial distances. This is illustrated in Fig. 10 for 2.5 AU. The solid curves merely reproduce the sweepup times of Fig. 8. The dotted lines are the time it takes a molecule or small particle to diffuse different radial distances, between $0.1H$ and $30H$, where H is the vertical scale height. It is meaningful to discuss radial diffusion by less than a scale height because the mixing lengthscale (the turbulence integral lengthscale) is $L = H\alpha^{1/2} < 0.1H$ for $\alpha < 10^{-2}$ (Cuzzi et al., 2001). Note from Fig. 10 that an ensemble of chondrules might never be able to clean out all the dust from a region much narrower than H, because it can be diffusively replenished from surrounding regions on shorter timescales than t^* for nearly all α. On the other hand, a region wider than H may be swept clean faster than the timescale on which fresh dust may be diffused into the region. Another way to state this is that the "closed environment" of Morfill et al. (1998) must be a scale height or more in radial width, if the nebula is turbulent.

If indeed the near-linear relationship between a chondrule's core volume and its rim volume is due to sweepup of all local dust, then a second implication follows that whatever process is responsible for primary accretion must operate on a timescale which must be short compared to the timescale on which a new ensemble of "fresh" chondrules are created—unless *all* chondrules in the volume were reprocessed. If this were not true, the newer chondrules would be unrimmed if sweepup were complete, or less rimmed if it were not yet complete. This would blur or eliminate the relationship between core size and rim thickness (Fig. 1). Whether the sweepup is complete or not will depend on the primary accretion timescale compared to the rimming timescale. If the primary accretion timescale is shorter than the rimming timescale, this becomes the common rimming time. This line of argument also seems to favor heating events at least a significant fraction of H in radial extent.

It also makes sense for the primary accretion timescale to be fairly short compared to timescales on which the nebula temperature and composition evolves (Cassen, 1996, 2000); if this were not true, we would not see such distinct classes of meteorites. Since most agree that $H/R \sim 0.05$, the timescales on which we might expect to see global evolution are comparable to the lines for $10H$ and $30H$ in Fig. 10. Thus, taking $\alpha = 10^{-3}$ for example, we would expect the primary accretion process to collect some local ensemble of coarse particles into planetesimals on a timescale which is probably longer than 10^3 years but probably much shorter than $10^5 \times (10^{-3}/\alpha)$ years.

Of course, the meteorite record is replete with complications for any theory. There are, for instance, a number of "igneous rimmed" chondrules (Rubin and Krot, 1996) which might be easily explained by a dust-rimmed chondrule experiencing a second chondrule-formation-like event. In the context of the present proto-scenario, these might represent the chondrules which escape primary accretion to experience a second chondrule-forming event. The relative abundance of such objects probably says something about the efficiency of the primary accretion process and its timescale relative to the recurrence time of chondrule formation events.

In order to test the hypothesis that sweepup by chondrules of fine grained dust, or more likely of fluffy aggregates of fine grained dust, is responsible for their fine-grained rims, we need a much better data set than currently exists. There are at least two different things that should be better determined:

(1) Does the general relationship which is *roughly* given by $V_{\rm rim} \propto V_{\rm core}$ (Paque and Cuzzi, 1997) extend to all samples and to all meteorite classes? That is, do OCs have the same functional relationship as CV and CM chondrites, differing only by a multiplicative constant (related perhaps to a shorter rimming time or to a smaller ambient dust density)?

(2) More precisely, what is the power of the dependence of $V_{\rm rim}$ on $V_{\rm core}$? This power is directly related to the *St* de-

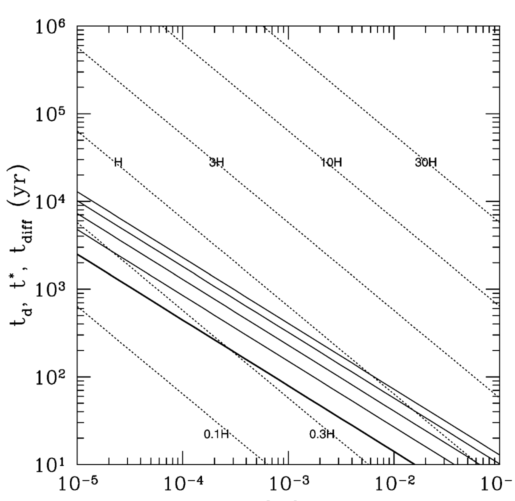

Fig. 10. An expanded version of Fig. 8 (solid lines) for the time it takes an ensemble of chondrules to sweep up all the dust in some region, now including the time it takes fine dust to diffuse radially by the amounts shown (dotted lines, labeled in terms of the vertical scale height H).

pendence of V_{pg}. If a slope of 0.75 could be definitively distinguished from a slope of 0.5 or 1.0, for instance, this would be very strong evidence that the rimmed particles were $St_\eta = 1$ particles (Section 1.2.1).

6. Summary

In this paper we developed a theory for accretion of fine-grained dust rims on chondrule-and-CAI sized particles, using the expressions for relative particle–gas velocity V_{pg} of Cuzzi and Hogan (2003). We noted how the near-linear dependence of $V_{pg}(r)$ translates into a near-linear dependence of $V_{\rm rim}$ on $V_{\rm core}$, as observed, if all particles in a meteorite share a common rim accretion time. Relying on theoretical modeling of velocity-dependent energy loss in collisions between porous, deformable aggregates (Dominik and Tielens, 1997) we estimated the sticking efficiency (moderate) and porosity (low) for rims on particles in this size range. We then estimated the time needed for chondrules to acquire rims as thick as those observed (100–1000 years within a factor of a few). We noted how CAIs probably lie in an entirely different regime than chondrules (incurring erosion, rather than accretion), under the same turbulent conditions, because of their larger sizes. We pointed out some qualitative implications regarding the timescales on which the as-yet-unknown chondrule formation and primary accretion processes may operate. We noted the need for new observations of fine grained rims, as a way to put further constraints on the environment of primary accretion. The association of near-linear rim-core dependence with particles in the chondrule size range, combined with our previously reported correspondence between predicted and observed chondrule sizes and size distributions, provides additional support for a weakly turbulent nebula (Cuzzi et al., 2001) as the environment of chondrule and CAI formation, evolution, and primary accretion.

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